BIOMECHANICAL ANALYSIS: EXPLORING GENDER-SPECIFIC DIFFERENCES IN VELOCITY-BASED STRENGTH TRAINING

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Abstract. The purpose of this study is to enhance the control of the efficacy of the exercise squat with a barbell during velocity-based strength training (VBST) for female and male athletes. This will be achieved through a biomechanical analysis utilising innovative technologies (within the framework of the project «Digital Twin»). Methodology. Two independent groups were compared to determine the differences in the optimal balance function and strength exercises technique biomechanical indicators between male (n = 24, age = 19.83 ± 3.06, height = 1.84 ± 0.12 m; body mass = 77.2 ± 5.4 kg) and female (n = 17, age = 20.11 ± 3.12, height = 1.78 ± 0.11 m; body mass = 58.12 ± 4.15 kg) athletes. To evaluate the degree of development of the balance function in athletes, standard and complex Romberg tests with open and closed eyes were conducted with the assistance of the Stabilan-01 complex. The innovative development of OpenCap permitted the analysis of the dynamics of movement in the execution of a squat with a barbell exercise by male and female athletes. Results. The application of cutting-edge biomechanical analysis technologies has transformed the field of VBST by offering real-time feedback and objective, data-driven methodologies. A statistically significant difference ($p < 0.01$) was observed between male and female athletes in terms of their balance function. The male athletes exhibited diminished Romberg coefficients, quality of equilibrium function, and angular velocity asymmetry coefficients relative to their female counterparts. Furthermore, male athletes exhibited a positive accumulated offset angle and higher asymmetry coefficients of the sagittal velocity component and the ratio of linear and angular velocities, whereas female athletes demonstrated negative accumulated offset angles. A biomechanical analysis of the squat with a barbell revealed that female and male athletes exhibited distinct centers of gravity, which influenced the recommended knee angles for each gender to ensure effective and safe execution. The implementation of OpenCap, a web-based software program, has revolutionized the analysis of body position during VBST. The 3D kinematic evaluation offers an economical and dependable alternative to conventional techniques, facilitating a deeper comprehension of athletes' movements and exercise methodologies. Conclusions. The biomechanical analysis of the squat with a barbell exercise in VBST for female and male athletes using OpenCap technology reveals significant differences in the location of centers of gravity between genders. These differences have significant implications for the recommendation of optimal knee angles during the exercise, with the objective of ensuring effective and safe execution for both female and male athletes.

Keywords: biomechanical analysis, velocity-based strength training, innovative methods, gender-specific, "Digital Twin," OpenCap.

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БІОМЕХАНІЧНИЙ АНАЛІЗ: ВИВЧЕННЯ ГЕНДЕРНИХ ВІДМІННОСТЕЙ У СИЛОВОМУ ТРЕНУВАННІ НА ОСНОВІ КОНТРОЛЮ ШВИДКОСТІ

Анотація. Мета. Дослідження спрямоване на оптимізацію контролю ефективності техніки виконання вправи «присід зі штангою» під час силового тренування на основі контролю швидкості спортсменів та спортсменок на основі біомеханічного аналізу з використанням інноваційних технологій (у рамках проєкту Digital Twin). Матеріал і методи. Порівнювали дві незалежні групи з метою визначення відмінностей у біомеханічних показниках оптимальної функції рівноваги та техніки виконання силових вправ у чоловіків (n = 24, вік = 19,83 ± 3,06, зріст = 1,84 ± 0,12 м; маса тіла = 77,2 ± 5,4 кг) та жінок (n = 17, вік = 20,11 ± 3,12, зріст = 1,78 ± 0,11 м; маса тіла = 58,12 ± 4,15 кг). Для оцінки рівня розвитку функції рівноваги у спортсменів використовували стандартну та складну проби Ромберга з відкритими та закритими очима за допомогою комплексу «Стабілан-01». Інноваційна розробка OpenCap дала змогу проаналізувати динаміку руху під час виконання вправи присід зі штангою спортсменами та спортсменками. Результати. Біомеханічний аналіз із застосуванням інноваційних технологій революціонізував силове тренування на основі контролю швидкості (VBST), забезпечивши зворотний зв'язок у реальному часі та об'єктивні підходи, керовані даними. Ми виявили статистично значущі відмінності ($p < 0,01$) між спортсменами та спортсменками щодо функції рівноваги. Спортсмени продемонстрували нижчі показники коефіцієнта Ромберга, якостей функції рівноваги та коефіцієнтів асиметрії кутової швидкості порівняно зі спортсменками. Ба більше, спортсмени мали позитивний накопичувальний кут зміщення та вищі коефіцієнти асиметрії сагітального складника швидкості та співвідношення лінійної та кутової швидкостей, тоді як спортсменки продемонстрували негативні накопичувальні кути зміщення. Біомеханічний аналіз вправи присідання зі штангою виявив різні центри тяжіння для жінок і чоловіків, що впливає на рекомендовані кути у колінному суглобі для кожної статі, щоб забезпечити ефективне та безпечне виконання. Використання веб-програмного забезпечення OpenCap змінило аналіз положення тіла під час VBST. Його тривимірна кінематична оцінка є доступною та надійною альтернативою традиційним методам, покращуючи розуміння рухів спортсменів і техніки вправ. Висновки. Біомеханічний аналіз вправи присід зі штангою у силовому тренуванні на основі контролю швидкості (VBST) для спортсменів і спортсменок за технологією OpenCap виявив значні відмінності в розташуванні центрів ваги між статями. Ці відмінності мають велике значення для рекомендацій оптимальних кутів у колінних суглобах під час вправи, щоб забезпечити ефективне та безпечне її виконання як для жінок, так і для чоловіків.

Ключові слова: біомеханічний аналіз, швидкісно-силове тренування, інноваційні методи, гендерні особливості, Digital Twin, OpenCap.

Introduction. In recent years, advancements in technology have revolutionized the field of sports biomechanics, allowing for accurate and detailed analysis of athletes' exercise techniques [1-4]. Innovative methods and applications, such as the «Digital Twin» project, have paved the way for gender-specific strength training load planning for elite athletes [5-7]. By leveraging digital technologies, researchers have assessed musculoskeletal function during various activities and provided recommendations for optimal training design to enhance the safety and efficiency of functional outcomes.

Nagorna V., Mytko A., Borysova O., Zhyhailova L., Achermann B., Lorenzetti S. Biomechanical analysis: exploring gender-specific differences in velocity-based strength training. Sport Science Spectrum. 2024; 2: 20–26
DOI: 10.32782/spectrum/2024-2-4

Нагорна В., Митко А., Борисова О., Жигайлова Л., Ачерманн Б., Лоренцетті С. Біомеханічний аналіз: вивчення гендерних відмінностей у силовому тренуванні на основі контролю швидкості. Sport Science Spectrum. 2024; 2: 20–26
DOI: 10.32782/spectrum/2024-2-4

However, the translation of digital technologies from biomechanics research to the strength training setting has faced challenges. Two key hurdles include the representation of individual subjects in digital human models and the lack of wireless technologies to capture motion data outside the research lab. These challenges have limited the widespread use and applicability of digital technologies in strength training.

Velocity-Based Strength Training (VBST) has gained significant attention in recent years as a method to optimize athletic performance [8-11]. Biomechanical analysis plays a crucial role in assessing athletes' exercise techniques and identifying areas for improvement. Our research work explores the use of applications and innovative methods for biomechanical analysis in VBST. It discusses the benefits of real-time feedback, motion capture systems, wearable sensors, and computer vision technologies. Furthermore, it highlights the importance of objective data-driven approaches in enhancing athletes' training experience and performance outcomes.

Biomechanical analysis plays a crucial role in understanding the nuances of human movement and performance. In the realm of strength training, specifically velocity-based exercises, it becomes essential to explore the gender-specific differences that may exist. This analysis aims to delve into the biomechanical aspects of velocity-based strength training exercises, focusing on the disparities observed between female and male athletes.

Purpose. Our study aims to optimize the control of the effectiveness of the technique of performing the exercise squat with a barbell during Velocity-Based Strength Training for women and men athletes based on biomechanical analysis using innovative technologies (within the framework of the project «Digital Twin»).

Material and Methods. ***Participants.*** Two independent groups were compared to determine the differences in the optimal balance function and strength exercises technique biomechanical indicators of male (n = 24, age = 19.83 ± 3.06, height = 1.84 ± 0.12 m; body mass = 77.2 ± 5.4 kg) versus female (n = 17, age = 20.11 ± 3.12, height = 1.78 ± 0.11 m; body mass = 58.12 ± 4.15 kg) athletes. The participants of the following study were recreationally active athletes with at least 2 years of experience in performing a squat with a barbell exercise before data acquisition. All participants were healthy and regularly physically active. All participants were aware of the study's objectives and agreed to participate.

Procedure. A comprehensive study was conducted between 2021 and 2023, assessing the balance function of elite athletes from various sports and countries. The performance tests measured the quality of the balance function with and without visual control. From March 1, 2021, to January 25, 2022, the study observed the indicators of balance function quality. Subsequently, from June 1 to August 1, 2023, a 3D kinematics and kinetics analysis of movement was conducted using videos captured by two smartphones and a MacBook. This analysis was made possible through the use of the innovative OpenCap application, which facilitated the affordable analysis of movement dynamics during squat exercises with a barbell for both male and female athletes, without the need for specialized equipment or software.

Biomechanical Methods for the Performance Tests. The present study utilized standard and complicated Romberg tests, specifically with open and closed eyes, to assess the level of balance function in elite athletes. The stabilographic complex «Stabilan-01» was employed to directly evaluate the kinetic stability of the body during the tests.

Various indicators such as displacement of the center of pressure spread along the axes, length of the statokinesiogram curve, movement assessment, quality of the balance function, area of the deviation zone, number of points scored, and errors with visual and verbal stimuli were measured.

The Romberg tests consisted of two parts: one with open eyes featuring visual stimulation using alternating-colored circles on a screen, and another with closed eyes involving sound stimulation using tone signals. This approach allowed for the qualitative assessment of biomechanical and psychophysiological gender differences among elite athletes. Student's parametric test was used for statistical analysis of the functional parameters of resistance in the athletes.

In addition to the Romberg tests, the study utilized advanced anatomically-based fitting to subject-specific data from 3D body scanning, validated against magnetic resonance imaging. This personalized multi-body dynamics model was developed to analyze specific training interventions. Innovative approaches such as OpenCap and special phone application programs were used in the analysis. OpenCap involves steps like camera calibration, video collection and processing, marker position estimation, kinematics estimation, and generating physics-based dynamic simulations of movements. The entire pipeline was implemented in Python (v3.7.10), with the help of a web application that guides users through each step. Cloud instances were used for computing purposes [12-14].

Statistical Analysis. Using the Student's parametric test, we evaluated the statistical significance between the studied indicators. To quantitatively compare two independent groups (women, n = 17; men, n = 24), we used Student's t-test for independent samples. Testing the hypothesis about the equality of the means of two samples from a normal distribution was performed under equal variances. Moreover, when determining the statistical significance of the difference between the athletes' indicators using the non-parametric Mann-Whitney test, a reliability level of 95% was assumed (significance level $p = 0.05$). Finally, all statistical hypotheses were tested at the $\alpha = 0.05$ significance level ($p < 0.05$), and mathematical and statistical processing and data analysis were conducted using Statistica (Statsoft, version 7.0) and Microsoft Excel 2010.

Results. Velocity-Based Strength Training (VBST) focuses on monitoring the velocity of an exercise to determine the effectiveness and optimal load for strength and power development. Biomechanical analysis is an integral part of VBST, as it provides insights into athletes' movement patterns, technique, and performance. Traditionally, biomechanical analysis required expensive equipment and extensive laboratory setups. However, recent advancements in technology have made it possible to perform accurate and detailed analysis using innovative methods and applications [15-19], such as:

Real-Time Feedback Applications. Real-time feedback applications have revolutionized the way athletes receive immediate information about their exercise technique. These applications utilize velocity data captured during the exercise and provide real-time feedback on metrics such as velocity, power output, and bar path. Athletes can use this feedback to make

immediate adjustments to their technique, ensuring optimal performance and injury prevention. Examples of popular real-time feedback applications include PUSH, GymAware, and Bar Sensei.

Motion Capture Systems. Motion capture systems have long been used in the field of biomechanics to analyze human movement. These systems consist of multiple high-speed cameras that capture the motion of reflective markers placed on the athlete's body or equipment. In VBST, motion capture systems can provide detailed information about joint angles, segmental velocities, and timing of movements. This data can be used to assess techniques and identify areas for improvement. Notable motion capture systems used in VBST include Vicon, OptiTrack, and Qualisys.

Wearable Sensors. Wearable sensors have become increasingly popular in sports biomechanics due to their portability and ease of use. These sensors can be attached to various body segments or equipment to capture data such as acceleration, velocity, and orientation. In VBST, wearable sensors can provide valuable insights into athletes' movement patterns and techniques. They allow for real-time monitoring of key biomechanical variables and can be used to track progress over time. Examples of wearable sensors used in VBST include accelerometers, gyroscopes, and inertial measurement units (IMUs).

Computer Vision Technologies. Computer vision technologies have opened up new possibilities for biomechanical analysis in VBST. These technologies use image and video processing algorithms to extract relevant kinematic and kinetic information from recorded videos. They can analyze exercise techniques, joint angles, and bar paths, and even detect muscle activation patterns. Computer vision technologies eliminate the need for expensive motion capture systems and provide a cost-effective alternative for biomechanical analysis. Notable computer vision technologies used in VBST include OpenPose, Kinovea, and Coach's Eye.

Objective Data-Driven Approaches. The use of applications and innovative methods for biomechanical analysis in VBST has shifted the focus toward objective data-driven approaches. By collecting and analyzing objective data, coaches, and athletes can make informed decisions about training protocols, exercise selection, and technique modifications. Objective data-driven approaches enhance the training experience by providing athletes with personalized feedback and allowing for individualized training programs. Moreover, they enable coaches to track progress, identify performance trends, and optimize training interventions.

So, to assess the level of development of the balance function of female and male athletes, we used such technology as "Stubilan-01": standard and complicated Romberg tests were used with open and closed eyes, using visual stimulation (e.g., alternating-colored circles) in the first case and sound stimulation (e.g., tone signals) in the second case. The posture of the athletes modeled the technique of the initial position during the exercise squat with a barbell.

The Romberg tests conducted using the «Stubilan-01» system revealed statistically significant differences ($p < 0.01$) between male and female athletes in terms of their balance function. The following indicators demonstrated notable disparities:

Romberg Coefficient: Male athletes exhibited a coefficient of 173 ± 3%, while female athletes displayed a coefficient of 216 ± 2% ($t = 12.29$).

This significant difference indicates variations in balance function between the two genders.

Quality of Equilibrium Function: The equilibrium function of male athletes measured 0.78 ± 0.06, whereas female athletes showcased a score of 0.98 ± 0.02 ($t = 3.5$). This discrepancy suggests gender-specific differences in the quality of balance during velocity-based strength training exercises.

Angular Velocity Asymmetry Coefficient: Male athletes exhibited an asymmetry coefficient of 49.7 ± 3.2, while female athletes had a coefficient of -3.9 ± 2.4 ($t = 13.37$). This significant difference implies dissimilarities in angular velocity asymmetry between the genders.

Accumulated Offset Angle: The accumulated offset angle for male athletes measured 44.6 ± 2.0, whereas female athletes showcased an angle of -4.63 ± 1.88 ($t = 17.67$). This notable contrast indicates variations in the offset angle during velocity-based strength training exercises.

Asymmetry Coefficient of the Sagittal Velocity Component: Male athletes displayed an asymmetry coefficient of 2.87 ± 0.31, while female athletes had a coefficient of -0.02 ± 0.22 ($t = 7.6$). This significant difference suggests gender-specific disparities in the asymmetry of the sagittal velocity component.

The ratio of Linear and Angular Velocities: Male athletes showcased a ratio of 1.85 ± 0.26, while female athletes exhibited a ratio of 0.88 ± 0.34 ($t = 2.25$). This significant difference implies variances in the ratio of linear and angular velocities between the genders.

Elite athletes constantly strive for optimal performance, and understanding the biomechanics of their movements is crucial for achieving this goal. Traditional biomechanical analysis methods, such as marker-based motion capture systems, have limitations in terms of accuracy, reliability, and cost-effectiveness. To overcome these limitations, innovative technologies, such as OpenCap, have emerged as game-changers in the field of sports science [20-24].

To further analyze the differences in body position between female and male athletes in Velocity-Based Strength Training exercises, researchers utilized an innovative web-based software called OpenCap. This software allowed for the evaluation of 3D kinematics and kinetics of the technique of performing the exercise squat with a barbell during Velocity-Based Strength Training for women (Figure 1) and men (Figure 2) athletes. The analysis was conducted using videos captured by two smartphones equipped with specialized applications.

The development of OpenCap revolutionized the analysis of movement dynamics by providing an affordable and accessible solution. Unlike traditional laboratory studies that require specialized equipment and software, OpenCap enabled researchers to measure the kinetics of various techniques in real conditions. Close correlations with laboratory studies further validated the accuracy and reliability of the software.

This study aims to investigate the nuances of the squat with a barbell exercise technique during Velocity-Based Strength Training (VBST) [25] for female and male athletes using biomechanical analysis facilitated by innovative technologies such as OpenCap [26]. The focus of the analysis is

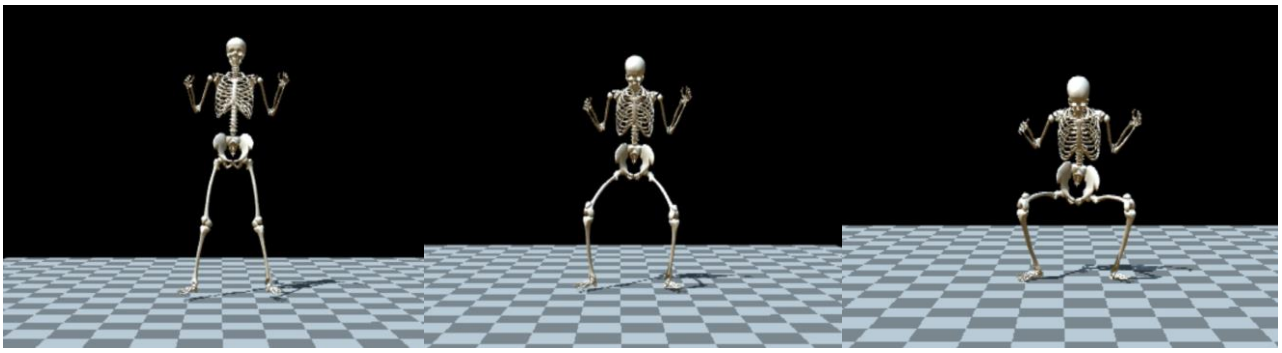

Figure 1. OpenCap 3D Kinematic Analysis of the Squat with a Barbell Exercise Technique for Female Athletes

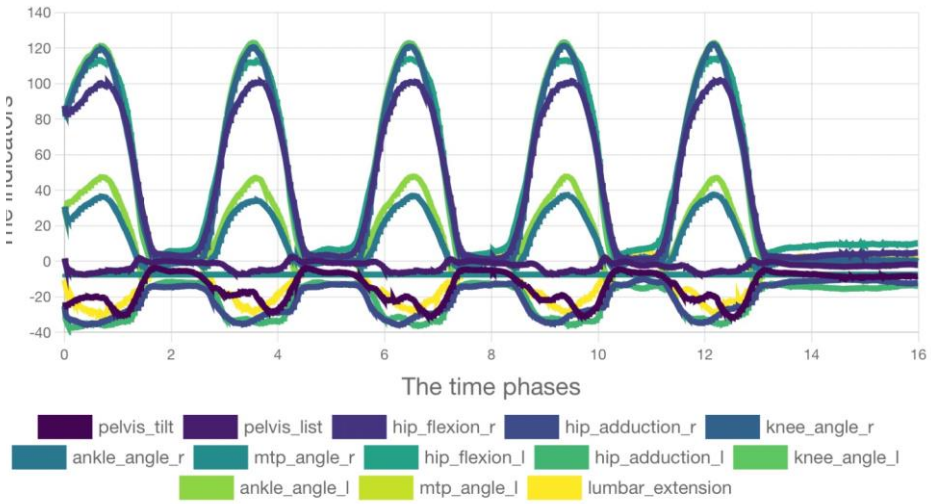

Figure 2. Comprehensive Analysis of the Squat with a Barbell Exercise Technique for Female Athletes

primarily on the location of the centers of gravity for women and men during this exercise. Our findings reveal that the center of gravity for women is predominantly located in the hips, while for men, it is considerably higher.

This difference in the location of the centers of gravity has significant implications for the recommended angles in the knee area for female and male athletes while performing the squat with a barbell exercise. Considering the varying centers of gravity, the optimal knee angles may differ between genders to achieve effective and safe execution of the exercise.

Furthermore, the present study builds upon data from various literature sources [27-30] and our previous investigations. Based on this information, we propose a hypothesis related to the impact of hormonal changes in different phases of the menstrual cycle on the speed of basic training in elite female athletes. The hormonal fluctuations during the menstrual cycle might influence strength and performance levels in female athletes, which could have implications for the execution of strength training exercises.

To explore this hypothesis further, we plan to conduct future research to assess the potential impact of hormonal variations on training outcomes in female athletes. This forthcoming investigation will provide valuable insights into optimizing strength training protocols for female athletes and contribute to a more comprehensive understanding of the role of hormonal fluctuations on athletic performance.

Discussion. The findings of this biomechanical analysis provide valuable insights into the gender-specific differences observed in velocity-based strength training exercises. The Romberg tests conducted with the «Stubilan-01» system allowed for the identification of significant variations in balance function between female and male athletes.

The disparities in the Romberg coefficient, equilibrium function, angular velocity asymmetry coefficient, accumulated offset angle, asymmetry coefficient of the sagittal velocity component, and the ratio of linear and angular velocities highlight the importance of considering gender-specific factors in training protocols. These findings can inform the development of tailored training programs that address the unique biomechanical characteristics of female and male athletes.

Understanding the biomechanical disparities between genders in velocity-based strength training exercises can lead to the implementation of more effective training strategies. By recognizing these differences, coaches, and trainers can tailor their programs to optimize performance and reduce the risk of injury.

Moreover, the study's findings and review of existing literature sources have allowed us to propose a hypothesis regarding the impact of hormonal changes during different phases of the menstrual cycle on the speed of basic training in elite female athletes. Understanding the potential influence of hormonal fluctuations on strength and performance levels could be crucial in tailoring strength training protocols to optimize female athletes' performance. To further explore this hypothesis, future research will investigate the effects of hormonal variations on training outcomes in female athletes. This

Figure 3. OpenCap 3D Kinematic Analysis of the Squat with a Barbell Exercise Technique for Male Athletes

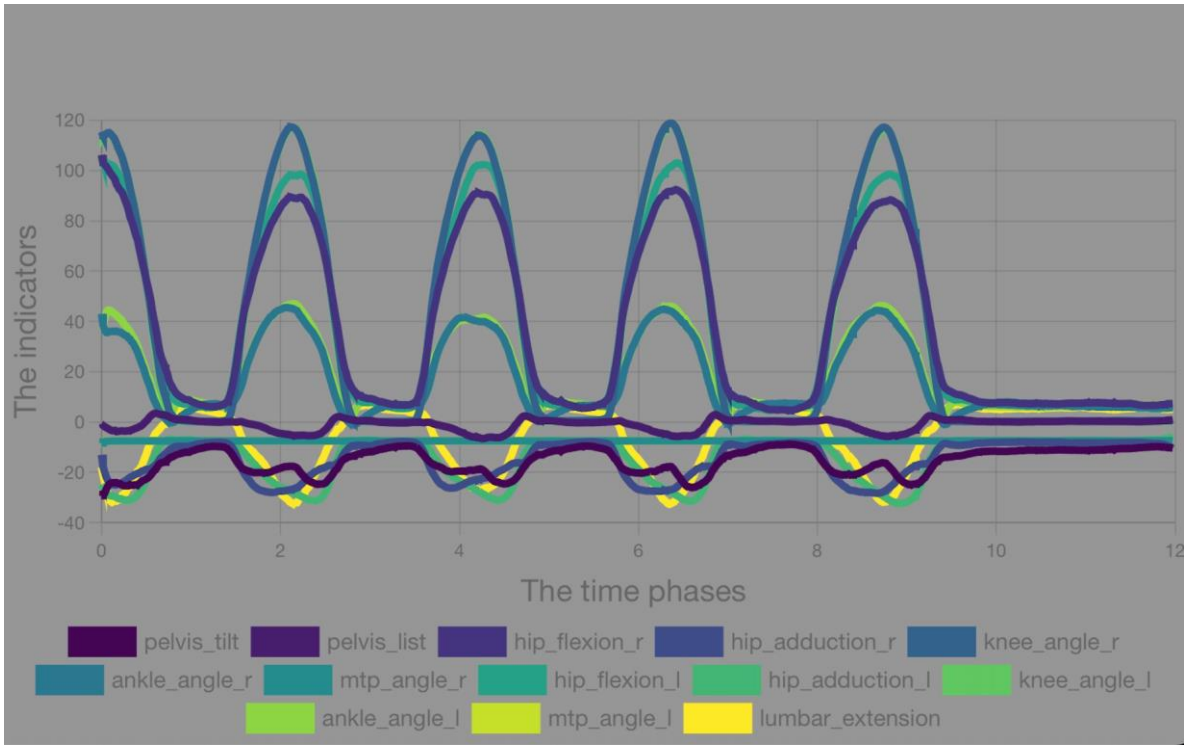

Figure 4. Comprehensive Analysis of the Squat with a Barbell Exercise Technique for Male Athletes

forthcoming investigation holds the promise of providing valuable insights into designing individualized training programs and advancing our comprehension of the role of hormonal fluctuations in athletic performance.

Combining biomechanical analysis using OpenCap and considering hormonal influences has shed light on crucial aspects of Velocity-Based Strength Training for female and male athletes. By gaining a deeper understanding of gender-specific biomechanics and hormonal factors, coaches and trainers can develop targeted training approaches to enhance athletes' performance and well-being. Ultimately, this research contributes to the advancement of athletic training methodologies, benefiting athletes across various sports disciplines.

Prospects for Further Research. Our further research will be aimed at improving the programs of special physical training for female elite athletes, considering the peculiarities of the influence of the biorhythms of the female body on the performance of specific exercises, especially concerning strength training and the use of innovative technologies as means of pedagogical control.

Conclusions

1. Biomechanical analysis plays a crucial role in optimizing athletes' exercise technique and performance outcomes in VBST. The advancements in applications and innovative methods discussed in this article have revolutionized the way biomechanical analysis is conducted. Real-time feedback applications, motion capture systems, wearable sensors, and computer vision technologies provide valuable insights into athletes' movement patterns, technique, and performance. The objective data-driven approaches facilitated by these technologies enhance the training experience and contribute to improved athletic performance. Future research should focus on further developing and refining these technologies to unlock their full potential in VBST.

2. The analysis of indicators of postural stability of athletes revealed (n = 17 women; n = 24 men) a higher coefficient of the balance function for female athletes compared to males (average Romberg coefficient for men = 173% ± 2.62 while for women = –216% ± 2.32) likely due to gender-specific differences in the location of the centers of gravity.

3. The biomechanical analysis of the squat with a barbell exercise technique for both female and male athletes highlighted important differences in the location of the centers of gravity. For women, the center of gravity was found to be predominantly situated in the hips, while for men, it was higher. Consequently, these differences have implications for the recommended knee angles during the exercise for each gender to ensure effective and safe execution.

4. The use of the innovative web-based software OpenCap has proven to be a game-changer in the analysis of body position differences between female and male athletes during Velocity-Based Strength Training exercises. By enabling the evaluation of 3D kinematics and kinetics of the «squat with a barbell» exercise in real conditions, OpenCap provided an affordable and accessible solution compared to traditional laboratory studies. The close correlations with established laboratory methods further validated the accuracy and reliability of this software.

Acknowledgments. The authors are grateful to all athletes and national coaches who participated in the experiment.

The study was conducted according to the plan of scientific research work of the National University of Ukraine on Physical Education and Sport for 2021–2025 under topic 2.2, "Improving preparation for the main macrocycle competitions of Ukrainian national teams in sports games" (state registration number 0121U108185).

The Swiss National Foundation SNF partially supported this study with the project funding of project 192289, "My digital twin is revealing the biomechanics of safe and efficient strength training".

Conflict of Interest. The authors declare no conflict of interest.

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